Operational challenges for long pulses on JET-ILW

OPEN ACCESS
IOP Publishing

Plasma Physics and Controlled Fusion

Plasma Phys. Control. Fusion **67** (2025) 085011 (12pp)

https://doi.org/10.1088/1361-6587/adf42c

Operational challenges for long pulses on JET-ILW

D B King[1,*], E Lerche[2], X Litaudon[3], S Brezinsek[4], E Joffrin[3], F Auriemma[5], M Beldishevski[1], N Balshaw[1], M Baruzzo[5,6], A Boboc[1], P Card[1], I S Carvalho[7], P J Carvalho[1], I Coffey[1], P McCullen[1], S Dalley[1], E Delabie[8], P Dumortier[2], R Felton[1], S Gerasimov[1], Z Ghani[1], A Goodyear[1], N Hawkes[1], R B Henriques[1], S Hotchin[1], P Jacquet[1], I Jepu[1], D Keeling[1], D Kinna[1], D Kos[1], E Litherland-Smith[1], R Lobel[1], P J Lomas[1], C Lowry[1], J Mailloux[1], M Maslov[1], D Matveev[4], A Meigs[1], S Menmuir[1], J Mitchell[1], I Monakhov[1], C Noble[1], M Poradzinski[9], F Rimini[1], S Silburn[1], E R Solano[10], H Sun[1], C Srinivasan[1], B Thomas[1], D Valcarcel[1], R Villari[1], J Waterhouse[1], A West[1], I Young[1], JET Contributors[11], the EUROfusion Tokamak Exploitation Team[12] and JET Operations Team[13]

[1] UKAEA, Culham Campus, Abingdon OX14 3DB, United Kingdom
[2] LPP-ERM/KMS, Brussels, Belgium
[3] CEA, IRFM, F-13108 St-Paul-Lez-Durance, France
[4] Forschungszentrum Jülich, IFN-1 Plasma Physics, 52425 Jülich, Germany
[5] Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy
[6] ENEA, Fusion and Nuclear Safety Department, C.R. Frascati, Rome, Italy
[7] ITER Organization, Saint Paul Lez Durance, France
[8] Oak Ridge National Laboratory, Oak Ridge, United States of America
[9] Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland
[10] Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain

E-mail: damian.king@ukaea.uk

Received 21 March 2025, revised 4 July 2025
Accepted for publication 25 July 2025
Published 5 August 2025

Abstract

The typical pulse on the JET tokamak is ∼10 s during the main phase of the discharge, however long discharge operation (>30 s) is possible with sufficient preparation and care. During the last period of JET operation in 2023 long pulses in deuterium plasmas were developed to assess the sustainment of the plasma performance over several times the current resistive time scale and to address plasma-wall interaction physics in a full metallic environment with the ITER-like wall, with a W divertor and a Be first wall. To prepare for the long pulse operation an analysis of heatloads was required to ensure the pulse was safe for the machine, this defined a number of choices on toroidal field and plasma configuration. While the 30 s pulse was within the control and protection systems commissioned operating envelope the target 60 s pulse was beyond the normal operation of the control and protection systems. These systems were adapted and tested

[11] See Maggi *et al* 2024 (https://doi.org/10.1088/1741-4326/ad3e16) for JET Contributors.
[12] See Joffrin *et al* 2024 (https://doi.org/10.1088/1741-4326/ad2be4) for the EUROfusion Tokamak Exploitation Team.
[13] See King *et al* 2024 (https://doi.org/10.1088/1741-4326/ad6ce5) for the JET Operations Team.
[*] Author to whom any correspondence should be addressed.

as far as possible to ensure they would work in the real pulse and a number of issues resolved over a series of tests. Significant modifications were required to carry out the experiment which had to be reversed before going back to standard operations. Even with these extensive preparations issues were found and resolved leading to the success of the 60 s pulse. The technical details of these preparations and their implementation will be discussed in detail.

Keywords: JET, long-pulse, fusion

1. Introduction

During the last and final period of JET operation in 2023, long duration pulses in deuterium plasmas were developed to assess the sustainment of the plasma performance over several times the energy confinement time close to the current resistive time scale, to address plasma-wall interaction physics in a full metallic environment with a W divertor and a Be first wall [1]. A key question raised by the international community is how to optimize the path to improve fusion performance in long-pulse regimes for future applications such as JT-60SA, ITER, volumetric neutron sources and fusion reactors. It has been reported that the fusion triple products as a figure of merit for the fusion performance (from a multi-machine database) has revealed a dramatic reduction of at least two orders of magnitude when increasing the plasma duration from less than 1 s to 100 s [2]. The data indicates that long-pulse operation is typically achieved in regimes dominated by electron heating but at reduced plasma density. This approach maximizes core electron heating and enhances the non-inductive current drive effect generated by external power sources. As a result, for durations typically exceeding 10 s, these regimes are characterized by reduced ion temperatures ($\leqslant$3 keV). Finding a pathway for long-pulse operation with large size devices like JET at higher densities and core pressures remains a key challenge that is addressed in these pioneering JET experiments. This data will contribute to the international multi-machine (tokamaks and stellarators) database on long pulse, managed by the Coordination on International Challenges on Long duration OPeration (CICLOP) group [2]. In addition, these experiments have provided new insight in the plasma retention process over long duration and new nuclear data in an integrated tokamak environement on the activation of the cooling water (cooling loop of the duct of one of the neutral beam system) due to high-energy neutrons flux [2–4].

Many of the systems on JET do not have the active cooling arrangement required to sustain steady state operation. The exact details of the systems are described in the subsequent sections but it should be noted that the wall is inertially cooled and that the divertor does not have sufficient cooling power to sustain steady state operation with constant material temperature requiring inter-pulse cooldown after reaching the maximum temperatures for the tungsten tiles.

Two types of long duration discharges were successfully developed for this purpose: (i) a 30 s ELMy H-mode with combined 12–14 MW neutral beam heating (NBI) and 2 MW of ion-cyclotron resonance heating (ICRH) and (ii) a 60 s long pulse with 4–5 MW of NBI and 2 MW of ICRH. Both operational scenarios are based on previously developed hybrid-like plasmas at JET [5, 6] with plasma current $I_P = 1.4$ MA and toroidal magnetic field on axis $B_0 = 1.9$T (safety factor $q_{95} \sim 4$). This was the first time that NBI system has been be used for durations longer than 30 s on JET.

To prepare for the long pulse operation an analysis of heat loads was required to ensure the pulse was safe for the machine, this defined a number of choices on Bt and plasma configuration. While the 30 s pulse was within the control and protection systems commissioned operating envelope, the 60 s pulse was beyond these systems' normal operational expectation. The control, diagnostic and protection systems were adapted and tested as far as possible to ensure they would work in the extended pulse and a number of issues resolved over a series of test pulses without plasmas, known as dry runs. A broad team of experts was convened to review all these aspects and support the long pulse operation on the days they were carried out. Significant modifications to several systems were required to carry out the experiment which had to be reversed before going back to standard operations. Even with these extensive preparations issues were found in the pulses, in particular on the heating systems and plasma shape controller. These were resolved leading to the success of the 60 s pulse.

As JET is a large, high-current tokamak capable of using tritium there is a requirement for a rigourous assessment of any operation against a set of well-defined operating instructions and a particular approval process required for operations outside these limits. This is possible because the unrestricted machine operational space is bigger than the operational space that preserves the machine integrity.

The scientific and operational aspects of these preparations and their implementation will be discussed in this paper, these will be split into the engineering and physical limitations and how to operate within them, the adaptations needed to the JET control systems and the approval process used. The results and physics analysis of the pulses will be shown separately [7].

2. Engineering limitations and pulse design

There are many limitations on pulse length and performance related to the design and operation of fusion devices. Previous work on long pulse operation has identified the individual areas of both engineering and physics limitations, these limitations can also interact with each other in complex ways.

In the preparation of the long pulses on JET a series of issues were identified in advance and then analysed to design the best possible pulse for fusion performance and duration that could be performed for 30 s and 60 s.

2.1. Toroidal field (TF)

The TF coils on JET are not superconducting but made of copper, hence there is a limitation on the magnitude of the field and the duration it can be applied related to the heating of the copper coils. Those coils are cooled by a heat-transfer liquid, Galden which is subsequently water cooled with additional cooling of this water available from a 6 MW chiller unit.

These limitations have been well analysed as part of JET operations and are considered in all pulse design. The maximum possible TF is 4 T, however only a small number of such pulses would be possible within the fatigue life of the coils. The ohmic dissipated energy in a pulse (to heating) is proportional to the square of the current flowing in the coils, I, and the time duration, (I^2 *x* time), and because the cooling power is much lower than the heating power during a pulse, the thermal stress created in the TF coils is proportional to the I^2t, which must be kept within safe limits. Time is subsequently needed to dissipate the heat between experimental pulses.

The allowed I^2t for a given pulse is considered against the total fatigue life and any pulse that would use more than 9×10^{10} A^2 s requires explicit approval and operation above 1.15×10^{11} A^2 s is not possible. For the maximum field of 4 T a current of 76 kA is required while for the 1.9 T used in the experiment a current of 36 kA is required.

For every pulse a prediction of the TF coil heating is made according to the programmed I^2t which then requires a certain starting temperature of the Galden is required to ensure that the temperature reached during the pulse will not exceed 70 °C in addition to the EM + thermal stress limit and poses additional constraint on I^2t. If this starting temperature is lower than can be achieved by the cooling system on a given pulse then the pulse cannot be started. Therefore the performance of the chiller system is an additional constraint on the possible TF that can be used.

The TF used will also relate to the possible ICRH scheme that can be used, only certain values of TF provide a good, central resonance and at very low values of TF a suitable ICRH frequency may not be available.

The TF on JET is supplied by a combination of static power supplies connected directly to the national grid and a flywheel that is wound up before the pulse. The PF is similarly powered by a flywheel and cooling of PF coils is not typically a concern on JET pulses.

2.2. Flux consumption

Current drive on JET is primarily ohmic, hence the pulse length that can be achieved will be related to the capability of the primary circuit and the resistivity of the plasma. To estimate the plasma resistivity, a test pulse at 1.4 MA/2.0 T was run and analysed and the flux extrapolated out to 60 s duration for a variety of possible loop voltages. By using a simple Spitzer resistivity this was related to the plasma temperature that would be required. This analysis can be seen in figure 1.

There are generally two breakdown modes on JET used depending on the current profile tailoring, flux consumption and *X*-point formation time of the proposed pulse. Both of these were candidates for the pulses although the optimisation for flux consumption was more important. It was decided to test both if possible but favour the optimisation for flux consumption. The flux consumption is similar for both modes, however the difference is in the amount of available flux. One breakdown only runs with positive primary current 0–40 kA, while the other can use the full swing from negative to positive currents. The breakdown mode with the full swing was chosen for the experiment

From this calculation it is seen that Te > 2.5 keV is required to reach the full 60 s desired. To achieve this temperature it is necessary to operate the plasma at a low enough density to achieve this temperature with the heating available. This estimate is a worst case extrapolation ignoring the bootstrap current and beam driven current.

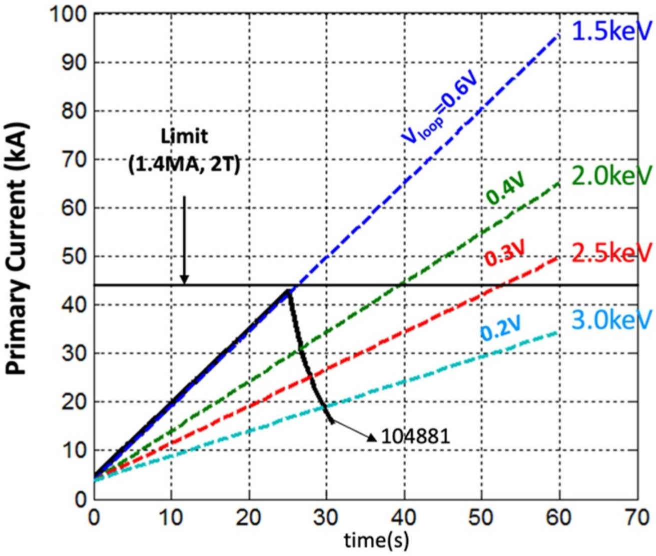

Figure 1. Primary current vs time for different estimates of resistivity.

2.3. Heating systems: neutral beam injection

One of the heating systems on JET is the NBI system. The NBI on JET is made up of two beamlines with eight injectors (known as PINIs) on each beamline. The beamlines are both in the co-current direction and are on opposite sides of JET.

In the previous long pulse operation on JET for 60 s the NBI was not used as NBI pulses duration longer than 10 s were not possible [8]. However, as part of the 2009 upgrade to the JET NBI system longer pulses of 15 s per PINI were now possible [9]. Given that there were multiple individual PINIs available it is possible to design a combination of PINIs in sequence such that 30 s and 60 s pulses could be achieved.

While there are many actively cooled components within the beamlines that can support very long or even steady state operation, there are also a number of inertially cooled and uncooled components that will limit the possible pulse length. Further to this, the heating of the JET inner wall by NBI shinethrough power also limits the operating space especially at lower density required to maintain lower plasma resistivity.

Within the NBI system the limiting components to extending beyond 15 s pulse length were identified as the molecular residual ion beam dump (known as the J-plate). While this component is water cooled there are areas of the dump that are further from the water cooling channel that can overheat, in this case >350 °C. During a pulse, as part of JET operation up to 2023 to protect this component, pulses of >15 s were prohibited.

There are also a number of inertially cooled components in the JET beamline that receive a significant power load. The exit scrapers from the beamline into the duct are such a component as well as some areas of the duct itself. The safe pulse length on these components could be extended by lowering the beam power, however this would have required too large a drop in beam power to provide a meaningful difference.

Beyond the beamline itself there are a number of power supplies that cannot extend much beyond 15 s. On the high voltage power supply there are some transformers that limit operation to 20 s, if the pulse were extended this far it may cause an issue, although by lowering the power this would likely be possible. Also the power supply for the filaments in the ion source in some cases are not suitable, while they should have been rated for at least 20 s in some cases only 12–17 s were possible.

There are many other components and challenges on the JET NBI system that would prevent operation at significantly greater than 15 s, however the above are the limiting cases and hence further limits were not explored in this exercise.

The beam shinethrough was analysed to determine how the best heating power could be achieved. Inner wall damage on JET is protected against by only permitting beam operation above a certain plasma density. To provide flexibility different limits on plasma density are applied depending on the pulse length and programmed beam acceleration voltage.

Given the severity of damage should there be excess shinethrough there are three separate interlocks on the density working at the same time. There are two interlocks that simply terminate the pulse if the density is below some limit and a more sophisticated real-time system based on a calculation of first wall component temperatures that terminates an indivudal PINI based on the particular footprint of that PINI.

The low density required to meet the flux consumption requirement provided a challenge to the shinethrough, but by examining the expected density it appeared that a beam voltage of ∼95 kV would be possible, providing ∼1.5 MW per PINI.

2.4. Heating systems: ICRH

The other heating system on JET is the ICRH system. This is made up by a set of antennas and generators to provide wave heating that can be used in a number of different heating schemes.

The arrangement of the generators and antennas has been varied over years of JET operations. To provide resilience against ELMs they are configured in such a way that the 4 antennas are energised in pairs; thus during the experiment only two independent generator sets could be used sequentially.

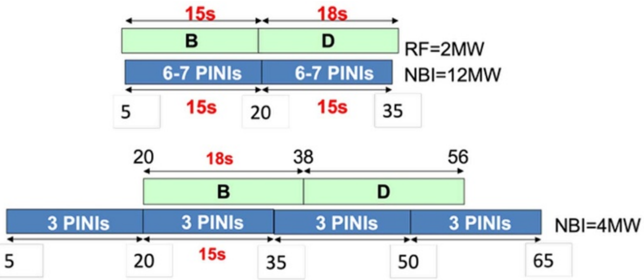

Figure 2. Heating power and timing planned for the 30 s and 60 s pulses.

The maximum pulse duration of the JET RF generators was originally restricted by the capabilities of high voltage power supplies at 20 s; shorter 18 s limit was introduced later due to enhanced volume of data processing within the RF real-time control system; hence with two independent RF systems a total of 36 s was possible.

The system can operate in a range of 25–57 MHz and hence a wide range of TF would be possible to use in the long pulse. However, the system reliability and achievable power is reduced at the extremes of this frequency range and when non-standard frequencies are used. Following discussion with the system experts a frequency of 29 MHz, hydrogen minority was proposed as the optimum heating scheme. This would correspond to a TF of 1.9 T and was used on both the 30 s and 60 s pulses.

2.5. Optimised heating mix for long pulse operation

Following consideration of both the NBI and the ICRH heating capabilities proposals for the heating in both the 30 s and 60 s pulses were made. In figure 2 a schematic of this heating proposal is shown. For the 30 s pulse the NBI power was split in two 15 s windows and the ICRH in one 15 s and one 18 s window to allow some heating to maintain plasma temperature through part of the ramp down and avoid a sudden HL back transition, giving ∼14 MW expected power. While for the 60 s pulse the NBI power was split in 4 with either 3–4 PINIs in each phase and the ICRH covering 36 s for 4–6 MW throughout.

There were further choices to be made in the heating setup, in particular when in the pulse to use the ICRH and how to split the PINIs used for charge exchange and motional stark effect diagnostics. This is further restricted by the way that the PINIs must be used in pairs due to the configuration of the power supplies and the bending magnet for the residual ions.

2.6. Heat exhaust

Once the plasma input heating energy has been considered it is important to investigate how to get that energy back out again. The heat is exhausted through the JET divertor structure, which is made of either bulk tungsten or tungsten coated CFC. The divertor structure is not directly cooled and hence there are limits on how much total energy can be injected into

Table 1. Tile energy limits on JET to limit fatigue of supporting structure.

Label	Green	Yellow	Orange	Red
Life in shots:	>33333	>3333	>333	<333
Input energy on tile 3 (MJ)	<171	171–232	232–324	>324
Input energy on tile 4 (MJ)	<155	155–213	213–303	>303
Input energy on tile 6 (MJ)	<108	108–168	168–315	>3115
Input energy on tile 7 (MJ)	<163	163–246	246–444	>444

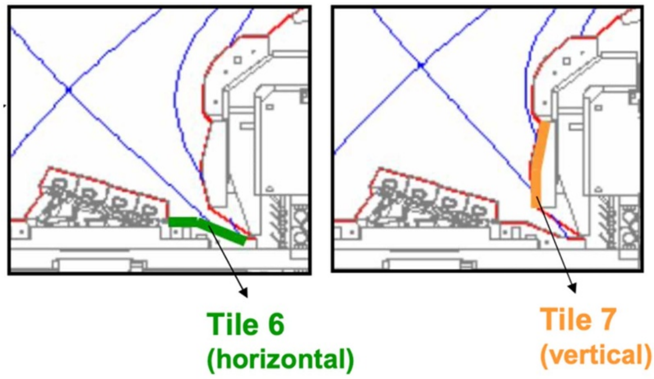

Figure 3. Layout of the JET divertor structure showing the regions of interest for this experiment.

the plasma before damage to the divertor components might occur.

As with the other systems there are a set of operating instructions that govern the heat allowed on the divertor. This takes the form of allowed surface temperature that is monitored by Infra-Red (IR) cameras and bulk material temperature, which is considered pre-pulse in a calculation of total energy on a given section of the divertor. The bulk limits are associated with fatigue on the structures supporting the divertor tiles and are shown for the different tiles in table 1. These limits are based on fatigue and temperature rise calculations and includes the assumption that the energy to the divertor is split with 1/3 to the inner divertor and 2/3 to the outer divertor. The radiated power is assumed to be 20% of the input power in these limits, and hence 80% in input power goes to the divertor. Typically on JET P_{rad} is $0.2\text{x}P_{\text{in}}$ and higher values of radiated power can only be considered in the safety assessment if extrinsic impurities are used.

Any operation in the orange or higher zones on JET are considered to use noticeable fatigue life and must be approved by the programme.

The main concern for the long pulses was the bulk heating on the outer divertor tiles used. This was primarily the corner target known as tile 6 and the vertical target known as tile 7 as shown in figure 3. However, for the higher power, 30 s pulse the inner tiles were also an issue and required a strike point movement to resolve.

It is possible to mitigate the heat loads on the divertor in various ways. A standard tool on JET to assist with the surface temperature is to sweep the strike point by 4–6 cm, however this does not aid the bulk temperature. The bulk temperature can be mitigated by moving from one tile to another, however the plasma performance is typically better on the corner tile due to increased effective pumping speed than other configurations. Finally, seeding of impurites to radiate more power is an efficient tool in reducing heat loads, however in this case it would have affected the resistivity and made the flux consumption a larger problem and as the use of impurities typically requires some optimisation this would have made pulse development more difficult.

Permission was sought initially for pulses within the orange zone and ultimately for pulses in the red zone. This red zone was entered in this experiment due to the high total input energy and has generally been avoided due to risk of fatigue related damage to the supporting structure of the tiles. In the context of the end of JET operations the programmatic risk from fatigue damage to the tile structure was considered acceptable.

2.7. Plasma scenario and pulse design

The experiment was to be carried out in a small number of sessions towards the end of the JET lifetime, hence it was decided to use a plasma scenario that was already well developed to avoid loss of valuable time in scenario optimisation.

The flowchart in figure 4 represents the decision path taken in developing the pulse. The additional heating and the TF were first considered together to arrive at a decision to operate at 1.9 T with 29 MHz H-minority ICRH.

There exists a large dataset on JET of pulses at 1.4 MA/1.7 T generated by hybrid plasma development, confinement scaling studies and isotope studies. The 1.9 T considered is close to this and 1.4 MA was shown to be compatible with expected flux consumption, hence 1.4 MA/1.9 T was chosen for the plasma current and TF.

Plasma scenarios at this field and current on JET are available with the divertor strike point on a variety of locations but the corner target was preferred as described above. The heating proposed in section 2.6 then drove the approach for the divertor configuration. For the 30 s pulse at higher power a phase on tile 6 and a phase on tile 7 was required to avoid bulk heating issues, while on the lower power, 60 s pulse the strike point would remain on tile 6 throughout.

Finally, the *X*-point formation, MHD avoidance, impurity accumulation strategy and gas dosing for ELM control were all

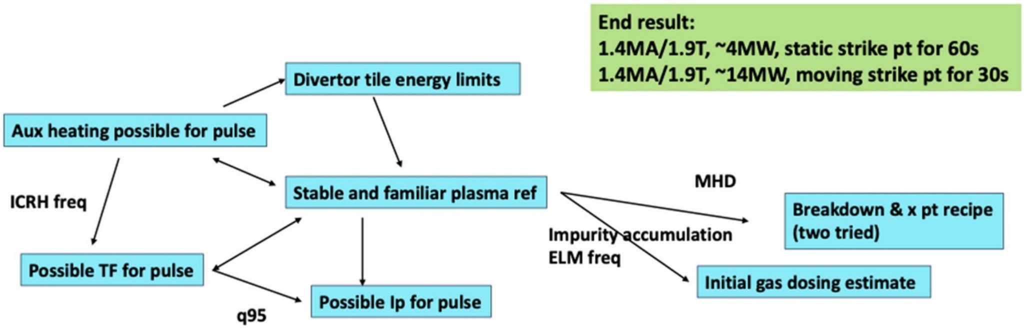

Figure 4. Diagram to demonstrate process of pulse design choices.

chosen from robust, recent references within the 1.4 MA/1.7 T dataset.

3. Control systems

The preparation of the control and diagnostic systems for the 60 s pulse was the largest amount of work involved in the entire experiment. The control systems on JET have been adapted and upgraded over a 40 year period, hence they cover a range of architectures and approaches. As there had been a previous 60 s pulse on JET in 1991 [8] it was certainly within the capabilities of the system to achieve this, but in that intervening time many changes had occurred, including some completely new systems.

Pulses on JET have the breakdown at 40 s due to the manner in which the various power supplies ramp up for the pulse. The pulse finishes at a time defined by the Plasma current decay (PCD) that is entered by the Session Leader and must be when the plasma current is 0.5 MA or below. Within the control system there is a limit on this parameter PCD that it cannot exceed 80 s. This limit was not a fundamental one related to the hardware or software capability, but a historical choice made that PCD $>$ 80 s would not be needed so 80 s would be a reasonable upper limit to set to avoid excessive pulse data storage requirements. As the 30 s pulse was within the standard limits it was only the 60 s pulse that this issue applied to.

The subsystems on JET take their end time for control and data acquisition from this parameter and in some cases had been configured such that they also could not exceed 80 s. Hence, although the JET systems were already capable in principle of achieving a long pulse, they were prevented from doing so by settings that had been chosen.

To resolve this a number of experts from the control and data acquisition system (CODAS) [10] team interacted with system responsible officers (ROs) to investigate each system for incompatibility with long pulse. The experience of the CODAS team with the overall system was essential to the success of this process.

The subsystems that were checked and found to require changes are shown in table 2. It is worth noting that as the control of JET is an integral part of the safety system and essential for machine protection great care was required in any intervention in them and any major changes to the functions would require time consuming re-commissioning that would not have been possible. Finally, any changes would need to be reversed on the return to normal operation.

Table 2. Subsystems of CODAS that required checking for 60 s pulse.

JET Supervisor software	High level control system known as ‘level 1’
TF settings and control	Controller and TF hardware—use of flywheel and user settings
Heating control	Software for NBI + ICRH
Magnetics	Diagnostics and control system
CODAS	Overall control system for JET, sets parameters for other systems
Thermal protection	Cameras and their interaction with the control system
Plasma control	Diagnostics and control system
Real time protection	Controller to protect against all off-normal events, many layers
Density control	Diagnostics and feedback loop controller
Vertical stabilisation amplifier	Concern over controller and amplifier overheating
DMS	Require MGI in pulse for protection
Plasma protection	More simplistic event handler
Hard wired protection	Even more simple protection directly on essential hardware

In the preparation numerous issues were considered and checked, the most notable ones are now described. The first consideration was the supervisor interface that allowed the users to control their systems, this is where the PCD parameter had to be set and a process for doing this agreed.

The control of the heating systems was a particular concern as many limits were found in the first check. While those were resolved it was not clear whether further issues would be uncovered in the final pulses when the heating could eventually be used.

The control algorithm for the TF must generate a solution using the flywheels and static units. However, this control system could not find a solution that would not exceed the maximum speed of the flywheel. Hence an expert mode using the static units only was required. As the field was only 1.9 T this was possible, however higher fields would have exceeded the capability of the static units.

There was a concern that magnetic diagnostic measurements (including plasma current) on JET would experience unacceptable levels of drift during the long pulse. The systems were checked and expected to be sufficiently robust against large drifts due to corrections implemented for previous long pulse experiments.

Due to the nature of the CODAS systems it was necessary to manually change a large number of parameters before moving to long pulse. This had to be done by the CODAS duty officer on the shift and could take 30–60 min to completely implement.

During the tritium clean-up that took place from 17/10/2023 to 24/11/2023 following the JET Deuterium-Tritium campaign (DTE3), several unusual pulse scenarios were run. From a control and data acquisition perspective, long pulse operation posed some interesting challenges. A normal JET pulse has 80 s of TF operation, 40 s of plasma and 10 s of neutral beam power heating at 30 MW. The TF limit was extended to 110 s with a plasma current of 1.4 MA. The neutral beam PINIs were sequenced to give 4–6 MW over 60 s and the RF heating system was sequence to give 2 MW over 40 s. CODAS memory limitations, sampling rates on the transient recorders for pulse-based data acquisition, explicit timings for control and data acquisition and heating system permitted operation had to be considered. Additionally, several implicit timeouts in the real-time control and protection systems had to be assessed and revised appropriately. While these long JET pulses were short compared to tokamaks with superconducting magnets and stellarators, where explicit memory and sample rate restrictions associated with transient recorders are not a problem due to the move to data acquisition by continuous streaming, there were implicit restrictions built into the control and data acquisition systems of JET alongside plant design, power supply and thermal limitations.

4. Diagnostics

The diagnostic systems were affected by the issues above and all had to be adapted to the PCD $>$ 80 s issue discussed above. This was done either by the diagnostic RO, the diagnostic coordinator or the CODAS duty officer depending on the details of the individual system. Some diagnostics are essential for the safe operation of the machine and some further diagnostics are essential for the scientific output of the experiment.

Beyond the issues with the settings there were further possible issues to overcome. The data storage available to diagnostics can be limited, particularly in stages in the acquisition process with limited buffer space. In the cases where the total amount of data caused an issue it was not possible to add more memory but instead it was necessary to reduce the acquisition rate at the price of lower time resolution. For certain diagnostics such as spectroscopy and probes the time window covered was reduced to a subset of the whole pulse.

The real time measurement of the plasma density required for the machine protection is provided by multiple interferometer systems. For the main one of these used as the first choice for normal plasma operations the control of the laser was not possible beyond 47 s. Thankfully, one of the older yet still functional interferometers was able to operate for the longer pulse with the use of a special, older control unit that had to be installed before the pulse. This was considered less robust so it did present a risk to the success as the loss of the interferometer will immediately terminate the pulse.

A further diagnostic related to machine protection is the IR wall protection camera systems. As these generate a large amount of data there was a concern that they may encounter a problem due to out of memory issues. While some of these cameras had a reduced time window there were sufficient cameras with enough data to cover the entire pulse.

5. Approval process, tests and sequence

The preparation for carrying out the long pulses began during the post-DTE3 [11, 12] cleanup with the first discussions on 23/10/2023. This phase of JET operation involved repeated use of robust JET plasmas to remove residual tritium from the in-vessel components.

As JET operates with rules, procedures and processes relevant for a fusion reactor environment the way in which the tests would be carried out had to consider a strict approval process. The initial preparations took the form of lead team members drawing up a list of possible issues to overcome and discussing these with ROs to determine what would need to be done. Following this information gathering a series of meetings with the relevant experts took place. The issues in sections 2–4 were identified during this process.

It was clear that a number of tests would be required before the full 60 s pulse could be attempted and also that as each test was successful new issues could be exposed. Agreement to proceed with these tests was sought from the JET Chief Engineer and the programme leadership responsible for the clean-up campaign.

The first tests went along two tracks, the first was to demonstrate a shorter version of the pulse that would be used to ensure a suitable plasma was ready while the second was to test all of the technical aspects of the extension to PCD $>$ 80 s. To test the second group here pulses without a breakdown to form a plasma were used, so called dry runs.

Due to the busy programme on JET, these had to be fitted within the clean-up campaign, the test plasmas were considered acceptable within the clean-up plasmas provided they injected sufficient power to progress the cleaning. An example of such a plasma, 105065 is shown in figure 5 where 30 s of lower power heating was applied in conditions anticipated for the final 30 s and 60 s pulses.

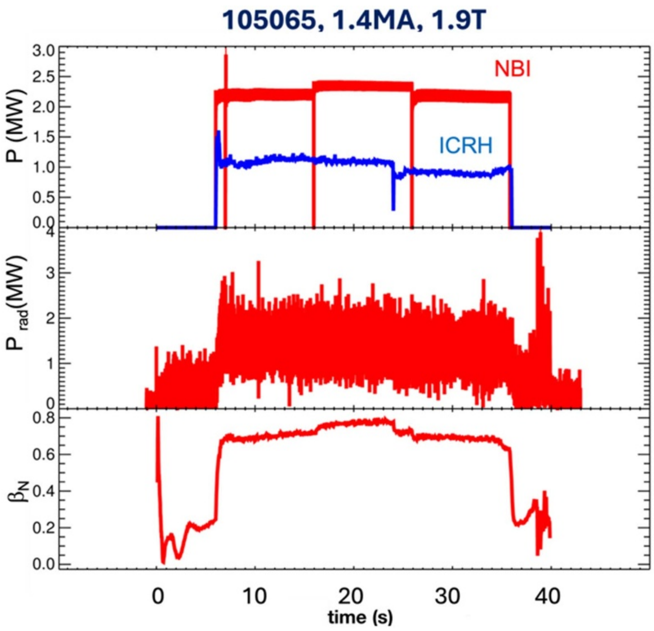

Figure 5. Input power, radiated power and normalised β for test pulse 105 065.

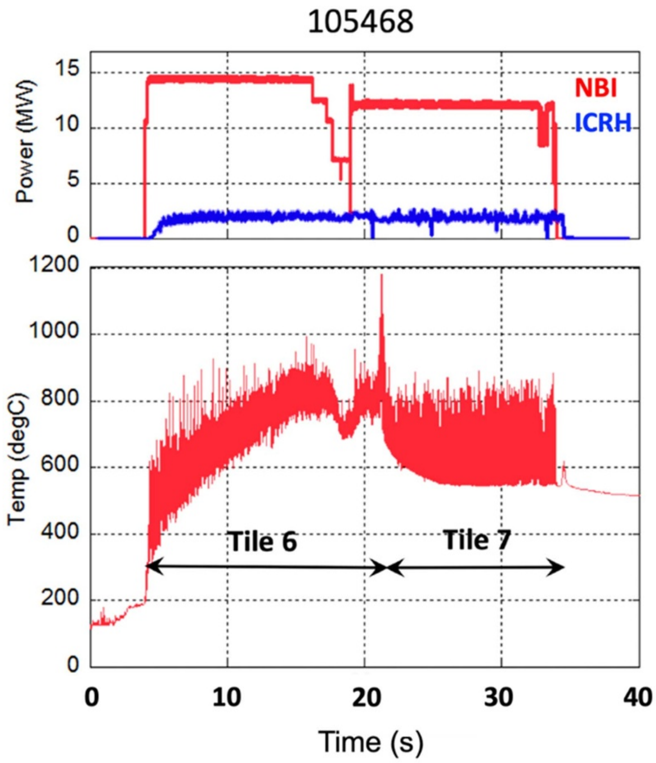

Figure 6. Input power (NBI in red, ICRH in blue) and maximum divertor temperature on each tile during a 30 s JET pulse.

The dry runs were more difficult to fit in so were performed during lunch breaks in the normal operations. This required the presence of all the people identified in sections 3 and 4 to be present and configure their systems accordingly.

Changes to key safety equipment and operations on JET require approval via a particular form signed by either the Chief Engineer and/or the Authority to Operate holder, these are responsible for plant safety and people safety respectively. In this case the Chief Engineer was the relevant authority. One blanket approval form was used for the long pulse tests with a checklist attached to cover the changes to each subsystem. This checklist also included the reversal of all the changes to allow subsequent routine operation.

On the first attempts the tests required ∼20 people to support them and took ∼60 min to reconfigure all the systems. There was also further preparatory work carried out before this period where possible, for example offline testing of individual codes by the CODAS team.

The first dry runs raised a number of issues that were resolved and then successfully tested on subsequent attempts. Once all issues with a dry run had been solved the move to a full plasma was ready.

6. Outcome and issues

The first plasma attempts took place within a dedicated session for long pulses on the 24/11/2023. Due to the limits on the number of pulses, the first priority was the higher power and 30 s pulses with the 60 s pulses given a second priority. The only significant issue with the 30 s pulses was the heating of the divertor tiles. It did raise concerns that the proposed approach (shift of the divertor strike point) to mitigate the tile temperature increase had a deleterious effect on plasma energy confinement time and consequently plasma temperature and resistivity.

An example of the tile heating and the shift from one position to the other is shown in figure 6. The outcome of the shift of the divertor strike point is reported within the related paper on the physics results within this same special issue.

Within this dedicated session the first 60 s plasma attempt was performed. Unfortunately (and somewhat unsurprisingly) this attempt failed. On setting up the NBI system it was not possible to load a pulse with the full 60 s duration due to settings within the NBI timing system. The plasma was run regardless to assess other problems but stopped when the NBI stopped as with a lower plasma temperature the plasma current could not be sustained. Limited personnel were available on this Friday night operation, so the issue was catalogued for resolution later and the 30 s pulses continued.

In setting up this 60 s pulse it was also clear that the full 1.9 T field would not quite be possible, the performance of the TF cooling system on the day was not sufficient and so the field was reduced to 1.85 T during the later phase of the pulse from 44 s onwards once ICRH power had stopped. This provided no issue to the overall outcome but meant that the pulse could be run.

At various opportunities in the following weeks further attempts at the 60 s were performed. These were spread out due to the JET programme but this was beneficial to the experiment as it allowed time between tests to resolve issues. The issue with the NBI timing was resolved with an adjustment

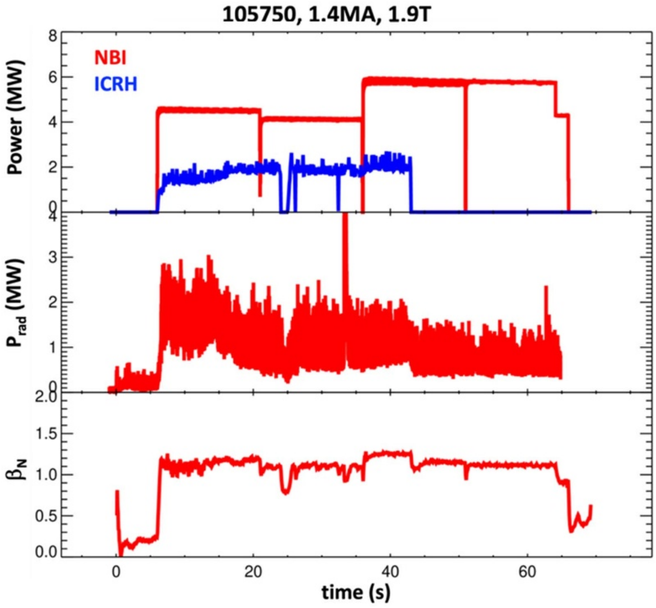

Figure 7. Input power (NBI in red, ICRH in blue), radiated power and normalised plasma beta for the full length, 60 s plasma.

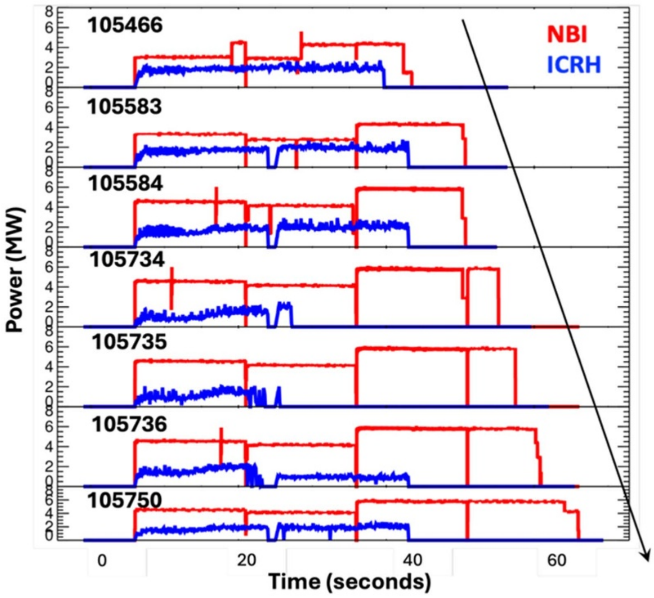

Figure 8. NBI and ICRH power for sequence of 60 s pulses attempted demonstrating the increasing duration achieved.

to the data acquisition speed by the NBI operator under the instruction of the CODAS expert.

In total there were 7 attempts at the 60 s pulse with the final attempt successfully making it all the way as shown figure 7. As a demonstration of the progress the NBI power for each pulse is shown in figure 8. The majority of the issues that had to be resolved were related to the heating systems.

The issues with each further plasma in figure 8 are as follows. Within pulse 105583 there was a stop at ∼50 s of JET heating triggered by the coil protection system. The alarm encountered was the check on the plasma current measurement. The instruments and plasma control system were examined and no obvious cause found. As no root cause was found immediately, a second attempt was made in case it was a spurious trip but the same issue occurred on pulse 105584.

During the period before the next session the plasma control, diagnostics and power supply experts discussed the issue and investigated further. On JET there is a drift compensation system that should have prevented such a trip from occurring. The plasma control expert located an issue in the code for this correction in which it was switched off after a fixed amount of time.

With this parameter adjusted a further attempt was made during a session to clean helium from JET following a diagnostic calibration. As with the post-DTE3 clean-up the long pulse was expected to provide efficient cleaning, however residual helium could also increase plasma resistivity.

The plasma control code adjustment was successful and the plasma 105734 continued to ∼55 s where the next issue was encountered. The second antenna on the RF system failed and the NBI system stopped again, this time with the cause appearing to be the magnetic field compensation system power supply. A discussion with the power supply expert revealed that the long pulse operation of this power supply is possible but that another setting in hardware was stopping the progress. A further attempt was made on pulse 105735 however the same issue occurred, the power supply expert made a further adjustment and on 105736 there was no trip related to this subsystem.

However, on this pulse one of the 3 NBI shine-through detection systems stopped the plasma just a few seconds later. A further discussion with the CODAS expert was required and the time allotted within the clean-up had run out so pulsing stopped at that time. The helium level in the plasma reduced by a factor of two in each successive pulse, this was not a goal of the session, but it is of interest in the overall discussion of long pulses on JET.

A final attempt was made possible later the same day, as only 3 d of JET operation remained this was likely the last chance. The CODAS expert had found that the NBI controller that converted a power waveform into beam on/off times was the cause. To change the software would have taken far too long so it was decided to run the NBI without this software in an older control mode not used since 2011, i.e. just programme a time per PINI rather than an overall power waveform. Cleaner plasmas now available also improved the chances of a hot enough plasma.

On pulse 105750 the full 60 s of NBI heating and 36 s of ICRH heating were successful. The plasma remained in H-mode for the whole 60 s planned.

From the complete dataset achieved in 30 s and 60 s plasmas the full results will be shown in the separate publication [7]. To demonstrate how these plasmas have expanded the range of operating space and greatly increased the energy to the divertor, the input energy against high power duration in the pulse is shown in figure 9.

There were further, more minor issues that occurred within these pulses. The cryogenic panel inventory software was not capable of dealing with long pulses initially and the total gas

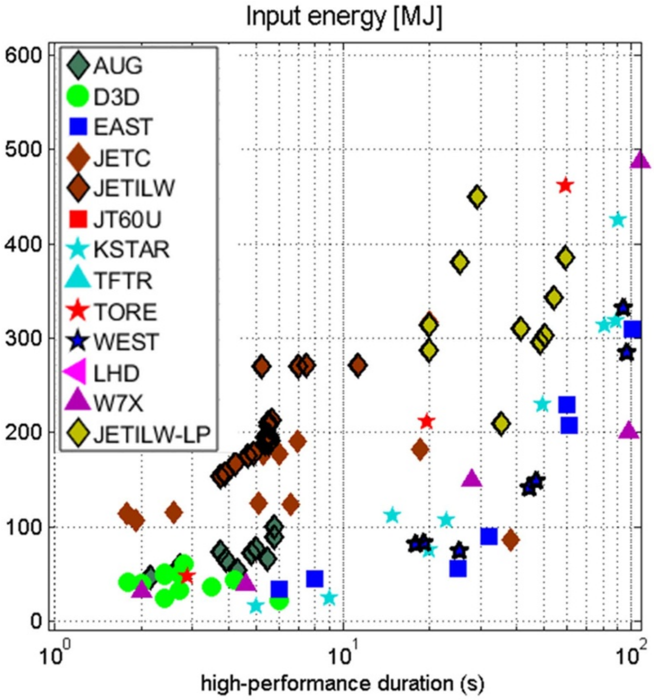

Figure 9. Input energy against high performance duration from the CICLOP database. JET-ILW pulses shown by yellow diamonds.

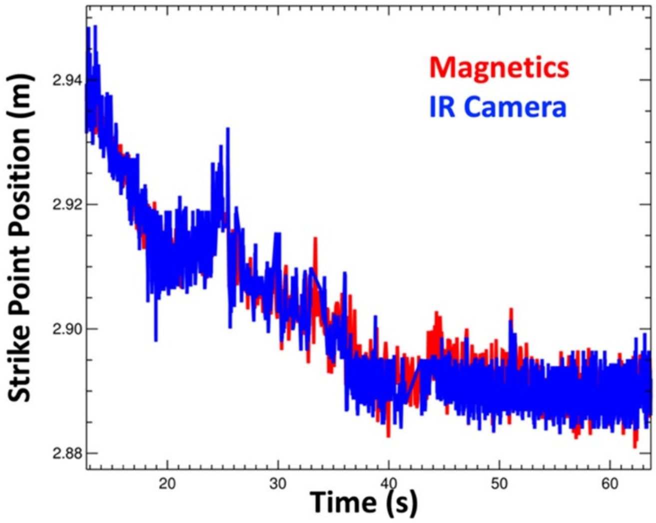

Figure 10. Strike point position in 60 s pulse as measured by IR and magnetic diagnostics.

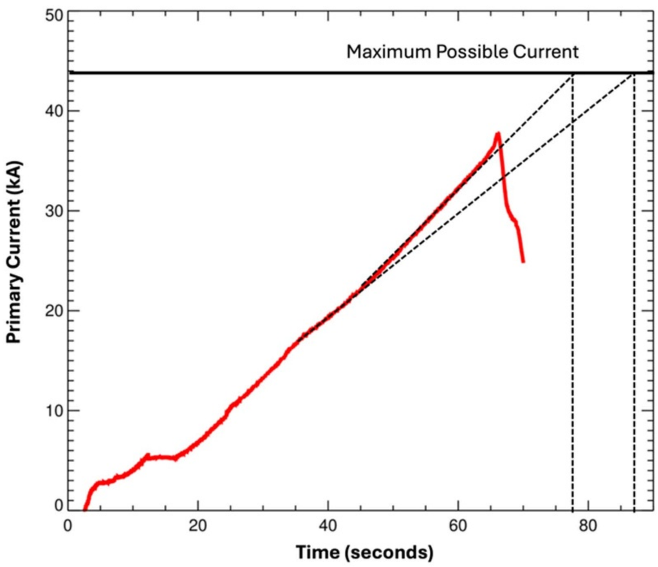

Figure 11. Primary current in successful 60 s pulse. Extraplolation to the current limit is shown from the highest power phase of the pulse and the last heated phase of the pulse.

inventory had to be entered by hand (in a conservative fashion) by the Session leader and Engineer in Charge.

As part of JET data collection there is a large amount of post-processing performed to provide the data in the form of a processed pulse file, or PPF. There were some issues with the production of the files during the sessions, this was also due to the way coding had been performed. In some cases the diagnostic officers produced a version of this that could be used in the control room while in others further work was required in the following period. As part of the data analysis all of these issues were resolved with the support of the diagnostic and CODAS teams.

As expected, there was some drift in the divertor strike point due to saturation effects. This was small however and did not cause an issue for the pulse, the strike point position is shown from IR and magnetic diagnostics in figure 10 to demonstrate this drift during the first ∼30 s of the pulse. It did not appear that the magnetic diagnostics themselves had an issue due to the appropriate level of compensation and correction in the system as the IR and magnetics do not drift apart during the pulse.

Unfortunately, on pulse 105750 some key diagnostics for scientific output failed at ∼45 s. This was not related to long pulse operation but there was no possibility to make further attempts.

6.1. Possible improvements

The primary limitation that prevented either >60 s pulses or a higher performance in the 60 s pulse came from the systems relying on inertial cooling and in particular the heating systems and their operation. The performance of the pulses completed that will be entered into the CICLOP database would have higher performance if the heating systems could have been operated longer or if a higher beam voltage had been possible without shine-through limitations.

If the heating systems could perform longer the pulse could have been extended slightly but soon either the TF or flux consumption limits would be hit. To extend the TF a further reduction in field strength would be required. The duration possible due to flux consumption can be estimated by extrapolating from the successful 60 s pulse. A very rough plot is made in figure 11 and it shows that depending on the heating phase extrapolated ∼80 s would be possible.

The performance of the plasma could have been improved with adjustments to the strike point control, gas dosing level and possibly other adjustments. However, there was no time to make such optimisations.

7. Conclusions

For the first time; high power and long plasma duration pulses of 30 s and 60 s heating phases have been successfully performed on JET with a metallic wall. The 60 s pulses in particular required a major effort from the JET operations team to make the various subsystems compatible with long pulse operation. That the pulse took only 7 attempts before being successful given all the issues involved is a remarkable feat that pays tribute to the knowledge and experience of the JET team.

A key conclusion from this work on JET long pulses is that the consideration of possible pulse limit during system design is vital. If the limitations related to PCD $>$ 80 s had not been present, then the amount of work required would have been significantly reduced and more time would have been available for plasma optimisation.

It should also be considered how the approval to extend pulses should be structured. Within this process on JET the approvals required at each stage were rigorous but not overburdening.

For the design of devices that consider long pulse operation there further engineering factors encountered on JET that should be considered, indeed some operational devices such as EAST or WEST have already considered these factors. For coils and their power supplies the move towards superconducting coils clearly makes long pulse operation easier, where conventional coils are used then sufficient cooling and power supply capacity for the planned should also be considered. External heating sources should be designed with active cooling on all components that will experience significant temperature rise during the pulse. Sufficient non-inductive current drive to maintain long pulse must also be modelled in advance and then installed.

Finally, as part of the CICLOP long pulse working group a number of topics have been identified as important to extension to long pulse [13], these are shown in table 3 split into machine and plasma limits in the way it has been presented previously. On JET a subset of these were encountered and are highlighted in green on table 3. They were: available flux, energy limit on coils, cooling system capacity (TF only), maximum duration of injected power, limits on divertor temperature (bulk rather than surface) and plasma measurement drift.

There are further topics that would arise on JET in even longer pulses, but within the experiment performed did not cause any problems. Those further topics are cooling system capacity beyond the TF, neutron limits, gas limits, impurity influx due to erosion or flakes and MHD stability.

This comparison against the CICLOP identified topics demonstrate that JET has contributed to the way long pulses can be operated on fusion devices and provided a leading example of how to extend from short to long pulses in a nuclear environment. Further to the topics in table 3, JET has also shown that it is vital to consider how pulse durations are handled in software and computer systems if long pulses are to be successful.

Table 3. Factors identified that must be considered for long pulse operation by the CICLOP group. Items in bold are those that have been explored in JET long pulses.

Machine/Wall limits	Plasma physics limits
Available flux	Pressure/Beta limits
Energy (I2t limit) or forces on the coils	Current instabilities
Max Energy to be exhausted by the cooling system	Disruption force
Max injected power reached	Pedestal pressure
Max duration of injected power reached	Core impurity (e.g. W)
Limit on wall/divertor temperature	Uncontrolled density (wall recycling)
Limit on heating systems	Density limits
Flakes or dust production	
Erosion, re-deposition and migration	
Current plasma measurement drift	
Neutron limits, Gas limits, other measurement limits	

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200—EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

This work has been carried out within the framework of the Contract for the Operation of the JET Facilities and has received funding from the Euratom Research and Training Programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

ORCID iDs

D B King 0000-0001-5128-5083
X Litaudon 0000-0001-6973-9717
S Brezinsek 0000-0002-7213-3326
E Joffrin 0009-0008-7527-0984
A Boboc 0000-0001-8841-3309

I S Carvalho 0000-0002-2458-8377
R Felton 0009-0002-2287-676X
S Gerasimov 0009-0002-3793-7211

References

[1] Matthews G F *et al* 2011 *Phys. Scr.* **2011** 014001
[2] Litaudon X *et al* 2024 *Nucl. Fusion* **64** 015001
[3] Radulovic V *et al* 2021 *Fusion Eng. Des.* **169** 112410
[4] Villari R *et al* 2024 Overview of deuterium-tritium nuclear operations at JET SOFT
[5] Hobirk J *et al* 2023 *Nucl. Fusion* **63** 112001
[6] Challis C D *et al* 2015 *Nucl. Fusion* **55** 053031
[7] Lerche E *et al* this PPCF issue
[8] The JET Team (presented by D. Stork) 1992 Plasma Physics and Controlled Nuclear Fusion Research *Proc. 14th Int. Conf. Wurzburg* vol 1 (IAEA) p 445
[9] Ćirić D *et al* 2010 *Fusion Eng. Des.* **86** 509
[10] Waterhouse J, Wheatley M, Stephen A, Hogben C, Jones G, Goodyear A, Farmer T and McCullen P 2025 *Fus. Eng. Des.* **210** 114737
[11] King D B *et al* 2024 *Nucl. Fusion* **64** 106014
[12] Maggi C *et al* 2024 *Nucl. Fusion* **64** 112012
[13] Belonohy E *et al* 2022 Operations knowledge management in the EUROfusion operations network *32nd Symp. on Fusion Technology (SOFT) (Dubrovnik, Croatia, 18–23 September 2022)* (available at: https://soft2022.eu/)